Prospects for Star Formation Studies with Mid-Infrared Instruments on Large Telescopes

Ray Jayawardhana

Department of Astronomy, University of California, Berkeley, CA 94720, U.S.A.

Abstract. Imaging and spectroscopic observations in the mid-infrared wavelength range (5μm–30μm) offer valuable insight into the origins of stars and planets. Sensitive new array detectors on 8-meter class telescopes make it possible to study a wide range of phenomena, from protoplanetary disks to starburst galaxies, in unprecedented detail. I review the capablities of ground-based mid-infrared instruments (e.g., high spatial resolution) and their limitations (e.g., poor sensitivity, small field of view) using several examples in the field of star formation, and discuss prospects for the near future.

1 Introduction

The earliest stages of star and planet formation are deeply shrouded in cocoons of gas and dust, usually impenetrable at shorter wavelengths. Mid-infrared radiation suffers relatively little extinction, and therefore provides a valuable probe for investigating these dusty beginnings. The 5μm–30μm range is ideal for observations of the thermal continuum emitted by warm dust with $T \approx$ 100-300 K, often found in the circumstellar environment, and of the spectral features due to a variety of atomic (e.g., [Ne II]), molecular (e.g., H_2, PAHs) and solid-state (e.g., silicates) species.

2 Promise

The great promise of ground-based mid-infrared instruments is their high spatial resolution. Since imaging in this wavelength regime is (almost) diffraction limited, large ground-based telescopes have a significant advantage over satellite observatories such as IRAS and ISO with their small primary mirrors.

3 Limitations

However, ground-based mid-infrared observations are challenging, to say the least, for two primary reasons:

- The atmosphere is only partially clear in the 5μm–30μm wavelength range. Since the atmospheric opacity is mainly due to absorption by water vapor and carbon dioxide, transmission significantly improves with dryness of the site and altitude.

- The background emission is dominant over the astronomical sources and variable on short timescales, making it necessary to continuously measure and subtract the sky. (A 300 K blackbody peaks at 10μm.) Integration times are very short (tens of milliseconds), and the use of chopping and nodding is essential.

As a result, observations are usually photon-noise limited and the sensitivity is relatively poor. Even on an 8-meter telescope, it is difficult to detect a point source fainter than 1 mJy (or mag$\approx$11.5) in the broad N-band centered at 10μm in a reasonable time. Cooled space-borne observatories –such as SIRTF– will have much better sensitivity.

While mid-infrared detectors have vastly improved over the past two decades, most arrays in astronomical use to date have been limited to 128$\times$128 pixels, providing a small field-of-view ($\sim$10”$\times$10”) on 8-meter class telescopes. The new mid-infrared instrument on the ESO 3.6-meter telescope, TIMMI2, marks a step forward with its 320$\times$240 Si:As array developed by Raytheon.

The other handicap of the current generation of mid-infrared instruments is their low spectral resolution, typically $R\approx$100 at 10μm. However, COMICS on Subaru achieves $R\sim$ 2000, and VISIR on the VLT is designed to do long-slit spectroscopy up to $R\sim$ 30,000.

4 Science: Results and Prospects

Despite these limitations, many important scientific results have been obtained in recent years through the use of mid-infrared instruments on the ground. The advent of 8-meter class telescopes enhance the science prospects for the near future.

4.1 Compact HII Regions

Continuum mid-infrared imaging is useful for tracing the distribution of warm dust emission within compact HII regions while narrow-band (e.g., [NeII]) imaging can help identify ionizing fronts. For example, Smith et al. (2000) have studied the mid-infrared morphologies of the W49A complex, located on the far side of the Galaxy and thus behind some $\approx$300 mag of extinction along the line of sight. Their images have sufficient resolution to investigate the nature of the dust emission from individual sources and make comparisons with the radio observations. As another recent example, Chini et al. (2001) produced a 20μm/10μm “temperature map” of the dust in the Orion BN/KL complex, and identified the main sources of heating.

4.2 Embedded Protostars

One of the difficulties of probing the formation of protostars is a deficit of high spatial resolution observations. Large extinction ($A_v \gg 10$ mag) usually prevents

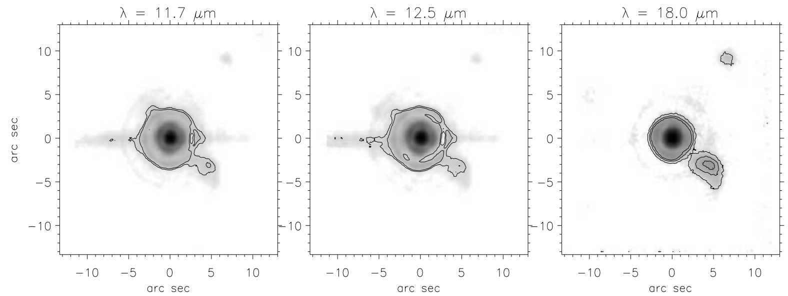

Fig. 1. IRTF/MIRAC3 images of AFGL 2591 at (a) 11.7μm, (b) 12.5μm, and (c) 18.0μm. Contours are plotted for 10 and 15 σ levels in panels (a) and (b), and for 5, 10 and 15 σ in panel (c). From Marengo et al. (2000).

optical imaging while millimeter observations typically have larger beam sizes. Mid-infrared imaging and spectroscopy can help.

For example, Marengo et al. (2000) have recently presented sub-arcsecond-resolution images of the high-luminosity young stellar object AFGL 2591 and its circumstellar enviornment. Their images, at 11.7, 12.5 and 18.0 μm, reveal a knot of emission ≈6” SW of the star, which may be evidence for a recent ejection event or an embedded companion star (Fig. 1). This knot is roughly coincident with a previously seen near-infrared reflection nebula and a radio source, and lies within the known large-scale CO outflow. Marengo et al. also find a new faint NW source which may be another embedded lower-luminosity star. The *IRAS* mid-infrared spectrum of AFGL 2591 shows a large silicate absorption feature at 10μm, implying that the primary source is surrounded by an optically thick dusty envelope.

4.3 Herbig Ae/Be Stars

First identified by Herbig (1960) as higher-mass counterparts to young T Tauri stars, these objects show many of the same signs of activity such as emission lines and large infrared excesses. Over the years, several authors have attempted to model their spectral energy distributions as dusty envelopes and/or disks (e.g., Miroshnichenko et al. 1999 and references therein). Recent mid-infrared imaging by Polomski (2001; Fig. 2) and others reveal companions and complex circumstellar environments around many of these sources.

4.4 Circumstellar Disks

The recent discovery of a spatially-resolved disk around the nearby 10-Myr-old star HR 4796A is a spectacular demonstration of the power of high-resolution mid-infared imaging (Jayawardhana et al. 1998; Koerner et al. 1998). The surface brightness distribution of the disk is consistent with the presence of an inner

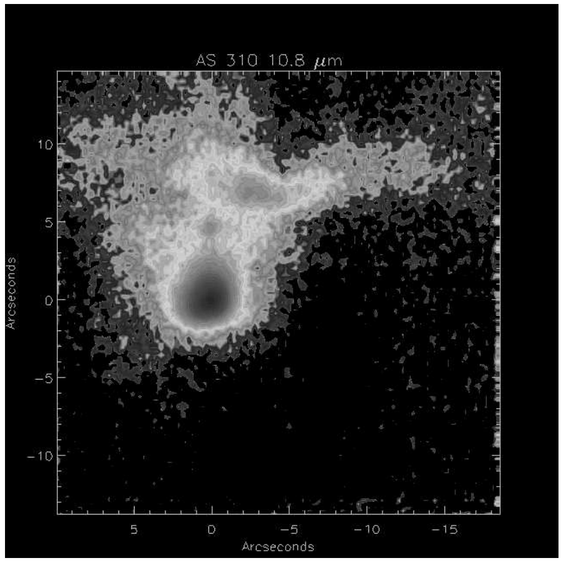

Fig. 2. IRTF/OSCIR image of AS 310 at 10.8μm, showing complex circumstellar structure. From Polomski (2001).

disk hole of ∼50 AU radius, as was first suggested by Jura et al. (1993) based on the infrared spectrum, and provides an important constraint on inner disk evolution timescales. Follow-up 10μm and 18μm observations on Keck also revealed tentative evidence for a brightness asymmetry in the disk (Telesco et al. 2000; Fig. 3) which may be the result of a forced eccentricity on dust particle orbits by a companion.

Mid-infrared spectroscopy, even at a relatively low resolution of $R \approx 100$, is a useful probe of disk mineralogy. In particular, the 10μm silicate feature of some disks appears to be rather similar to that of comets in the solar system (e.g., Knacke et al. 1993). There is also some evidence, albeit limited to small samples, for evolution of the silicate feature over timescales of several million years (e.g., Sitko et al. 2000).

One of the exciting prospects for the near future is nulling interferometry at 10μm on the Keck Interferometer and VLTI, with the possibility of detecting (somewhat higher-surface-brightness) counterparts of the zodiacal cloud around nearby stars. Hinz et al. (1998) have already demonstrated nulling on an astronomical target with two segments of the MMT.

4.5 Starburst Galaxies

Observations in the thermal infrared have the potential to identify the luminosity source in so-called "ultra-luminous infrared galaxies" determining the size of the emitting region. In many cases, the sources are unresolved, rather than extended, implying that they are either very compact starbursts or dust-enshrouded active

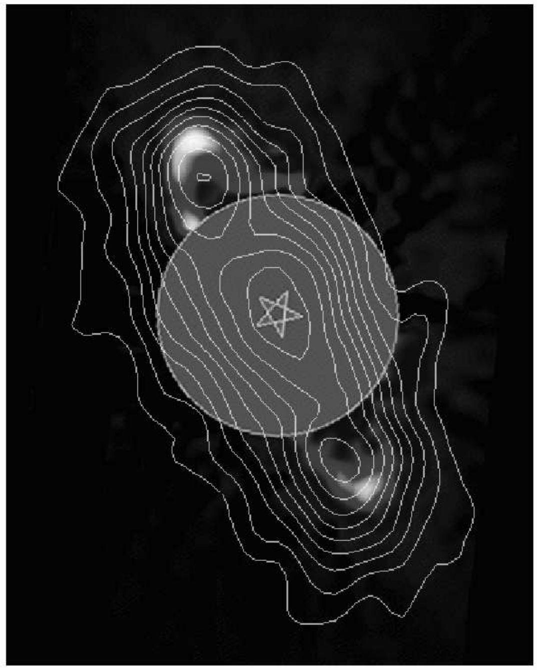

Fig. 3. Overlay of Keck/OSCIR 18.2μm contours on the 1.1μm HST/NICMOS coronagraphic image of HR 4796A disk. From Telesco et al. (2000).

galactic nuclei (e.g., Soifer et al. 2000). In some starburst galaxies, such as NGC 7469, there is evidence for a starbursting ring surrounding an AGN (Jayawardhana et al. 1997) and in the case of NGC 253, a "super star cluster" (Keto et al. 1999).

References

1. R. Chini, et al., in preparation (2001)
2. G.H. Herbig: ApJS, **4**, 337
3. P.M. Hinz, et al.: Nature, **395**, 251 (1998)
4. R. Jayawardhana, et al.: 'Infrared Imaging of the Starburst Galaxy NGC 7469'. In: *Star Formation Near and Far*, ed. by S.S. Holt, L.G. Mundy (AIP Press, New York 1997) pp. 303-306
5. R. Jayawardhana, S. Fisher, L. Hartmann, C. Telesco, R. Piña, G. Fazio: ApJ, **503**, L79 (1998)
6. M. Jura, B. Zuckerman, E.E. Becklin, R.C. Smith: ApJ, **418**, L37 (1993)
7. E. Keto, et al.: ApJ, **518**, 183 (1999)
8. R.F. Knacke, S.B. Fajardo-Acosta, C.M. Telesco, J.A. Hackwell, D.K. Lynch, R.W. Russell: ApJ, **418**, 440 (1993)

9. D.W. Koerner, M.E. Ressler, M.W. Werner, D.E. Backman: ApJ, **503**, L83 (1998)
10. M. Marengo, R. Jayawardhana, G.G. Fazio, W.F. Hoffmann, J.L. Hora, A. Dayal, L.K. Deutsch: ApJ, **541**, L63 (2000)
11. A. Miroshnichenko, Z. Ivezić, D. Vinković, M. Elitzur: ApJ, **520**, L115
12. E. Polomski: PhD Thesis, University of Florida, Gainesville (2001)
13. M.L. Sitko, D.K. Lynch, R.W. Russell: AJ, **120**, 2609 (2000)
14. N. Smith, et al.: ApJ, **540**, 316 (2000)
15. B.T. Soifer, et al.: AJ, **119**, 509 (2000)
16. C.M. Telesco, et al.: ApJ, **530**, 329 (2000)